Landscape and Urban Planning 182 (2019) 1–11

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Impacts and adaptation options for estuarine vegetation in a large city

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ARTICLE INFO

Keywords:
Mangrove and saltmarsh
Sea-level rise
Coastal squeeze
Estuary
Strategic planning
Spatial landscape modelling

ABSTRACT

Climate change adaptation options for natural systems are particularly challenging in high density urban settings. We model the vulnerability of estuarine vegetation (mangroves, saltmarshes and *Casuarina* forest) to sea-level rise in Australia's most populous city, Sydney, and conduct a detailed assessment of impacts and adaptation options for a densely urbanised estuary, the Cooks River. Our modelling demonstrates a range of opportunities for the preservation and, in some cases, expansion of estuarine vegetation area under sea-level rise, though this is largely dependent on the degree of flexibility applied in the management of existing open space. Mangrove area increases under a high sea-level rise scenario, more so than under a low sea-level rise scenario, due to opportunities for landward colonisation. However, this would require estuarine vegetation expansion and land-use conversion of recreational, industrial or private land. Sediment nourishment emerges as a potentially cost-efficient means of preserving wetlands. The mix of wetland types is likely to change without active management, with higher proportion of mangrove and substantially less saltmarsh under all scenarios. Implementation of living shorelines, as opposed to hard defensive structures, could be incentivised. This could be achieved by planning concessions, 'payment for ecosystem services' such as managing 'blue carbon' values, and zoning controls that promote visual amenity and ecological adaptation.

1. Introduction

Climate change and its effects on sea level, ocean currents, storms, rainfall, run-off and hydrodynamics along coastal margins is of particular concern for managers tasked with protecting both natural and built assets. In Australia, where more than 85% of the population lives within 50 km of the coast (Trewin, 2004), climate change is and will continue to be a key threatening process. As cities are dominated by buildings and associated infrastructure, research attention has largely focussed on the effects of climate change on built assets. However, natural assets also have significant environmental, social and economic value (Barbier et al., 2011). The most recent estimate of the value of global ecosystem services indicated substantial economic value for functions such as climate regulation, nutrient cycling, erosion and sediment retention, and refuge for commercially important and non-commercially important fauna (Costanza et al., 2014). In addition, urban ecosystem services will differ from those occurring in regional areas primarily due to greater use by a larger population and their contribution to public health and quality of life for urban populations (Bolund & Hunhammar, 1999). Spatial land use planning has a significant influence on the delivery of ecosystem services in urban landscapes and planning for the effects of climate change on natural assets will be essential for the protection, maintenance and creation of urban ecosystem services.

Sydney, Australia's most populous city, provides a unique case study for exploring the effects of climate change on ecosystems in urban settings and the services they provide. With a large population clustered along the coastline and estuarine shorelines, urban ecosystems are restricted in their distribution. This is particularly the case for intertidal ecosystems, such as mangrove and saltmarsh, for which natural distribution is already restricted to the upper half of the tidal range, approximately between mean sea level at the seaward margin and highest astronomical tide at the landward margin (Rogers, Boon, Lovelock, & Saintilan, 2017). Like other urban areas, the distribution of mangrove and saltmarsh is contained within the margins of urban sprawl, with significant losses associated with land-cover conversion from wetland to other land uses. In addition, developments at wetland margins restrict landward expansion of wetlands, progressively constraining the

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https://doi.org/10.1016/j.landurbplan.2018.09.022
Received 10 October 2017; Received in revised form 30 August 2018; Accepted 30 September 2018
Available online 16 October 2018
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space available for estuarine vegetation and termed 'coastal squeeze' (Doody, 2004; Pontee, 2013). However, unlike other Australian cities, the distribution of mangrove and saltmarsh is further constrained by factors inherited from the geology of the Sydney Basin. In this regard, sediment delivery during the Quaternary period to the deeply incised drowned river valleys of the Sydney Basin (Roy et al., 2001) was not high enough for formation of expansive depositional environments suitable for the establishment of large mangrove forests and saltmarsh plains (Saintilan & Rogers, 2013). Consequently, mangrove and saltmarsh development within Sydney Harbour, Port Hacking and the Hawkesbury River is restricted to narrow margins along these drowned river valley estuaries or within small fluvial delta regions, where bedrock depth is shallow and hydrodynamic energy is low enough to facilitate sediment deposition and vegetation establishment.

The mangrove and saltmarsh extent in the Sydney region is also a highly reduced remnant of its pre-European extent. It is difficult to estimate the original area of mangrove and saltmarsh across the region, but significant developments up until the 1970′s resulted in the conversion of large areas of mangrove and saltmarsh for commercial, residential and recreational facilities. They have also been converted to municipal waste disposal areas (locally known as tips) in the Georges River, Cooks River, Parramatta River and Lane Cove River areas. Examination of early plans and documents (McLoughlin, 1987, 2000a, b) has suggested that sedimentation associated with land clearing for development provided fresh habitat for mangroves head-ward of their pre-20th century extent in the Lane Cove and Parramatta Rivers. This has resulted in the conversion of portions of saltmarsh to mangrove since earliest European settlement. Comparison of historic and aerial photography has established a consistent increase in mangrove extent and subsequent saltmarsh decline in intertidal flats across the region (Saintilan & Williams, 1999). This documented decline has prompted the listing of coastal saltmarsh as an endangered ecological community in three NSW bioregions, including the Sydney Basin bioregion (*NSW Threatened Species Conservation Act*, 1995). The cause of mangrove encroachment into saltmarsh across southeast Australia is being investigated and is consistent with a global trend of mangrove proliferation at poleward limits of mangrove range (Saintilan, Wilson, Rogers, Rajkaran, & Krauss, 2014). Best available science for the southeast Australian region suggests changes in relative sea level are likely to have been an important driver (Kelleway et al., 2016; Rogers, Wilton, & Saintilan, 2006).

Mangroves and saltmarshes are responsive to climate change due to their position within narrow zones defined by tidal regime and mean sea level and their sensitivity to changes in atmospheric carbon dioxide, temperature and rainfall (McKee, Rogers, & Saintilan, 2012). Many of the changes evident over the past few decades are consistent with responses to climate change and associated sea-level rise (Cahoon et al., 2006; Rogers, Saintilan, & Heijnis, 2005; Woodroffe et al., 2016). For example, mangrove surface elevation gain has matched the rate of sea-level rise in the Sydney Harbour estuary since 2000 (Saintilan and Rogers in prep), suggesting that, in this site at least, the wetland is capable of remaining *in-situ* under current rates of sea-level rise (circa 3.4 mm per annum). However, the adjacent saltmarsh has not gained elevation over the 10-year period, reflecting the lower capacity of saltmarsh to gain elevation, a characteristic that appears to be consistent across the region (Rogers et al., 2006). These results suggest that sea-level rise is a factor contributing to the observed expansion of mangrove into adjacent saltmarsh and that this trend is therefore likely to continue as sea level continues to rise. The limited capacity of the upper intertidal zone to gain elevation relative to a rising tidal prism may also facilitate landward expansion of the wetland over time. Under low to moderate rates of sea-level rise, it is possible for mangrove and saltmarsh wetlands to increase in extent if unimpeded by barriers to dispersal (Rogers, Saintilan, & Copeland, 2013).

A stepwise approach to assess opportunities and challenges for estuarine vegetation management in the Sydney region was undertaken. This included a first-pass broad-scale assessment of mangrove and saltmarsh vulnerability for the Sydney Coastal Councils Group region using the vulnerability framework advocated in the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). This framework defines vulnerability as a function of the i) exposure and ii) sensitivity of a system to climate change, and iii) the capacity of a system to adapt to climate change (Parry, Canziani, Palutikof, van der Linden, & Hanson, 2007). Using this framework, and building upon other first pass assessment approaches (Rogers & Woodroffe, 2016), choropleth maps of mangrove and saltmarsh exposure, sensitivity and adaptive capacity were generated, with specific reference given to the influence of climate change on coastal processes that cause inundation and erosion. Subsequent integration of these maps provided an overall indication of the vulnerability of mangrove and saltmarsh to climate change.

Medium-resolution assessment of mangrove and saltmarsh vulnerability to sea-level rise was then conducted for the Cooks River catchment. This was undertaken using a readily available spatial model (Clough, Park, & Fuller, 2010; Craft et al., 2009) that could be used to provide an indication of the extent of estuarine vegetation under a range of sea-level rise, management and land-use scenarios. Medium-resolution modelling of the vulnerability of estuarine vegetation within the Cooks River was examined testing a variety of sea-level rise scenarios based upon those of the IPCC Fifth Assessment Report (IPCC high-RCP8.5, intermediate-RCP4.5 and low-RCP-2.6). Recognising the limitations of spatial modelling of the response of estuarine vegetation to sea-level rise (Mogensen & Rogers, 2018), consideration was given to changes within Wolli Creek, a tributary of the Cooks River. The modelling was informed by vertical accretion measures from the nearest Surface Elevation Tables (Rogers, Saintilan, & Cahoon, 2005) and tidal levels recorded along the Cooks River. We model the impact of coastal squeeze by comparing the projected extent of tidal flat, mangrove, saltmarsh and *Casuarina* while (i) allowing for encroachment of vegetation on built areas and (ii) prohibiting landward encroachment into built areas, those areas defined to have an urban or industrial land-use.

Sea-level rise adaptation approaches for coastal shorelines, including mangrove and saltmarsh, were subsequently considered; and we identified specific adaptation needs of mangrove and saltmarsh in the Sydney region. Adaptation options and the locations where such options might be implemented were recommended, and the principles and practices related to these adaptation options are discussed.

2. Methods

2.1. Study site

The study focussed on estuarine vegetation (mangrove, saltmarsh and *Casuarina*) occurring within the local government areas of the Sydney Coastal Councils Group, a regional organisation of councils (SCCG) (Fig. 1a and b). To identify potential pathways for expansion of estuarine vegetation along estuaries, the study area included all estuarine vegetation associated with the SCCG as well as low-lying land associated with Wolli Creek. This study focussed on low-lying sediments that have accumulated over the Quaternary period and upon which mangrove and saltmarsh develop (Fig. 1c).

Medium resolution assessment was data intensive and therefore restricted to a small spatial extent. The Cooks River, the most highly urbanised estuary of the Sydney region, was chosen as the focus study site for further modelling (Fig. 1d). The Cooks River is a mature, wave-dominated estuary, which enters the large coastal embayment of Botany Bay. Characteristic of wave-dominated estuaries, the estuary entrance has been infilled with sediment over time forming a coastal barrier that restricts both flood and ebb-tides into the estuary and results in measureable tidal attenuation along the estuary (Roy et al., 2001). Our reasoning for using this study site was that if climate change adaptation for estuarine vegetation is achievable in the Cooks River, it

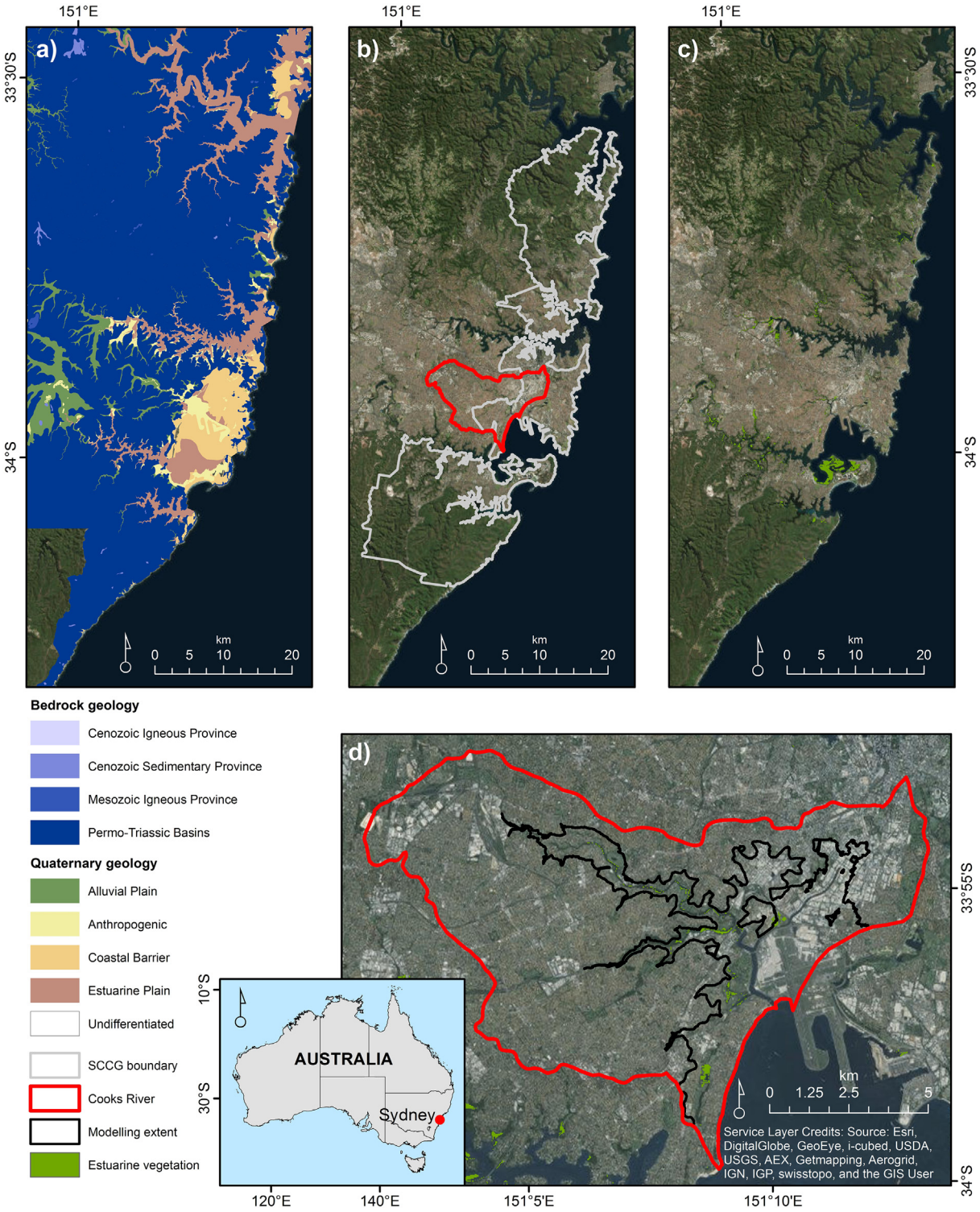

Fig. 1. The study site location and features of the study site, including a) bedrock and Quaternary geology of the Sydney Basin, b) extent of the Sydney Coastal Councils Group regional organisation of councils and the Cooks River study area, c) extent of estuarine vegetation within the Sydney Basin, and d) catchment of the Cooks River, the site of our medium-resolution assessment.

could potentially be accommodated elsewhere in Australia.

2.2. Broad-scale vulnerability assessment

The broad-scale vulnerability assessment focussed on biophysical aspects of vulnerability and builds upon a previously established approach (Rogers & Woodroffe, 2016). The initial assessment used a raster-based approach within GIS using the ArcGIS spatial analyst extension. Input datasets were used as proxy indicators of estuarine vegetation exposure, sensitivity and adaptive capacity. These included:

- *Shuttle Radar Topography Mission-derived 1 s Digital Elevation Model (SRTM-DEM)*. This was the primary dataset for characterising exposure of coastal landforms to the effects of inundation and erosion.

The SRTM-DEM dataset was also used to derive the slope of landforms to indicate the sensitivity of landforms to inundation. The Slope function in ArcGIS was used to generate the *Slope* surface, the resulting slope surface being a function of the spatial resolution of the input dataset. The SRTM-DEM is a raster surface with a cell size of approximately 30 m with elevation extrapolated from measurements to the nearest metre.

- *Coastal Quaternary geology mapping.* This was the primary dataset for characterising the sensitivity of coastal landforms to inundation and erosion. The NSW Coastal Quaternary Geology, which was prepared by the NSW Department of Mineral Resources as part of the Comprehensive Coastal Assessment of Southern NSW (Troedson, Hashimoto, Jaworska, Malloch, & Cain, 2004), was recently revised to incorporate the Sydney metropolitan area (Troedson, 2015) and constitutes a significant increase in the coverage of coastal Quaternary geology mapping of NSW. This mapping differentiates lithified (bedrock) from unlithified Quaternary sediments that are more sensitive to erosion. Quaternary sediments can be further classified on the basis of the depositional environment in which they were accreted, which enables discrimination of the finer fluvial sediments from the coarser marine sediments that deposit under high energy conditions and may be less sensitive to erosion due to their mass.
- *Sydney's salty vegetation mapping.* This was the primary dataset for characterising the adaptive capacity of coastal ecosystems to inundation and erosion. This dataset was originally prepared by OEH (2013) and a subset of 53 vegetation communities were selected by the Working Group of the SCCG Sydney's Salty Communities program following a series of workshops with member councils within the Sydney Coastal Councils Group. Vegetation communities pertinent for this assessment and which incorporated mangrove, saltmarsh and *Casuarina* forests included i) Coastal swamp paperbark-swamp oak scrub, ii) Estuarine swamp oak forest, iii) Estuarine saltmarsh, iv) Estuarine reedland, and v) Estuarine mangrove forest. These communities were used to differentiate salinity tolerance and their capacity for building elevation, binding sediments and buffering wave action. This data set was used to indicate the capacity of ecosystems to adapt to increasing exposure to coastal processes that cause inundation and erosion.

Composite choropleth maps were prepared that provided a relative indication of the vulnerability of estuarine vegetation in the study region to i) inundation and ii) erosion. To generate these maps, input raster surfaces were processed according to the geomorphological and ecological criteria detailed in Table 1. The extract function was used to select relevant cells from the input datasets. These cells were then reclassified and assigned a value of 1–3 depending on whether the extracted cells were indicative of high, moderate or low exposure, sensitivity or adaptive capacity. Only three cell values were used as this simplified processing of raster surfaces and ensured that each component of vulnerability received equal weighting. The composite choropleth maps characterising inundation and erosion vulnerability were generated by adding raster surfaces that characterised the exposure, sensitivity and adaptive capacity of cells using the raster calculator tool, with cell scores ranging between 1 and 9 for both choropleth maps. Low cell scores indicated lower vulnerability to either inundation or erosion. A final raster surface of the vulnerability of cells to both inundation and erosion was compiled by adding the original cell scores for inundation and erosion using the raster calculator tool to create an integrated raster surface with cell scores ranging between 0 and 18. To assist with reporting of vulnerability, cell scores were reclassified into five classes ranging from low to high vulnerability. The purpose of reclassification was to provide a relative indication of vulnerability that was qualitative and without bias, but did not provide an absolute or quantitative indication of vulnerability.

As the approach considered both ecological and geomorphological factors contributing to the vulnerability of mangrove and saltmarsh, the assessment broadly applied to depositional areas, as defined by Quaternary geology mapping, and was not limited to areas that currently support mangrove and saltmarsh. The initial assessment therefore did not account for the occurrence of built-up areas or incompatible land-uses. It also did not account for the effect that sea-level rise may have on the future distribution of mangrove and saltmarsh. Consequently, the assessment was constrained using masking techniques in ARCGIS to exclude any built-up areas or areas of incompatible land-use. The analysis also specifically considered estuarine vegetation distribution being constrained on the basis of a) current estuarine vegetation distribution, and b) possible future distributions of mangrove and saltmarsh associated with sea-level rise. Masking was undertaken using the *BuiltUpAreas* shapefile within the *Coastal Quaternary geology mapping* package, and current vegetation distribution using *Sydney's salty vegetation mapping*; and on the basis of *90 cm water level projections* data layer derived for the study area (McInnes, Lipkin, O'Grady, & Inman, 2012).

2.3. Medium-resolution assessment of the Cooks River

The medium-resolution assessment of mangrove and saltmarsh vulnerability to sea-level rise was undertaken using the Sea Level Affecting Marshes Model (SLAMM). SLAMM is one of the most widely used mangrove and saltmarsh focused spatial landscape models and simulates six primary processes affecting the survival of estuarine vegetation with long term sea-level rise, namely inundation, erosion, overwash, saturation, salinity and accretion. The model is used primarily to simulate the changes in wetland boundaries and shoreline modifications with increasing sea level through the inundation and accretion functions (Clough, Polaczyk, & Propato, 2014; Galbraith et al., 2002; Linhoss, Kiker, Shirley, & Frank, 2014).

As mangrove and saltmarsh communities lie within narrow elevation ranges associated with tidal inundation, it is important to consider tidal attenuation when modelling the effect of sea-level rise on the Cooks River. The parameterisation of tidal range within SLAMM, which is conceptualised as a flat surface with no slope, however, does not sufficiently capture the tidal effects throughout the estuary (Mogensen & Rogers, 2018). This can be improved by discrete parameterisation of tidal range in SLAMM, thereby partially accounting for the effect of tidal attenuation on vegetation distribution. To do this, a continuous tidal range surface was created for the model extent of this study from which discrete tidal range values were derived on a subsite basis and implemented within SLAMM. The tidal range surface was developed following OEH (2014), incorporating three, yearly-averaged tidal range values derived from MHL (2012) and a tidal range value derived from Oregon State University tidal inversion software or OTIS (Egbert & Erofeeva, 2010). From the resulting surface, subsites were delineated based on 0.1 m variations in tidal range along the Cooks River (Fig. 2) and a discrete, mean tidal range value was calculated from each subsite to be utilised within SLAMM.

SLAMM requires information regarding elevation, slope, vegetation communities, elevation boundaries of these communities, accretion rates for the wetland vegetation and an historic trend in sea-level rise. Topographic data in the form of Lidar (light detection and ranging) point files and derived digital elevation models (DEM) were the primary input data for SLAMM. The Lidar survey of the Cooks River region was flown in 2013 and the derived DEM utilised in this study has a horizontal spatial resolution of 5 m and the Lidar survey has a reported vertical accuracy of 0.3 m. A slope surface was derived from the 5 m DEM and utilised within the model.

Vegetation input into SLAMM is based on categories of the US National Wetlands Inventory (Cowardin, Carter, Golet, & LaRoe, 1979). Analogous vegetation classes and spatial distribution of the vegetation classes were derived from digital mapping of the *Native Vegetation Communities of the Sydney Metropolitan Area* (OEH, 2013). Vegetation

Table 1
Input data sets, explanation of data need and cell characterisation (label and description) for raster layers of inundation and erosion exposure, sensitivity and adaptive capacity. Cell label scores were assigned to raster surfaces on the basis of the indictors and their relationship to various components of vulnerability. Choropleth maps for each vulnerability component were developed on the basis of cell scores.

Effect	Component	Input data	Explanation	Cell label	Cell description
Inundation (I)	Exposure (IE)	Elevation (SRTM-DEM)	Lower elevations more exposed to inundation by proximity, higher elevation less exposed. Based on bath-fill approaches that have been widely used as an indicator of vulnerability (e.g. DCC, 2009). Rogers, Saintilan, and Copeland (2012) demonstrates why bath-fill approaches do not constitute a high resolution, quantitative assessment.	High (3) Mod. (2) Low (1) Nil (0)	Elevation: 0–1 m Elevation: 1–2 m Elevation: 2–5 m Elevation: > 5 m
	Sensitivity (IS)	Quaternary geology (OEH, 2013) Slope (SRTM-DEM derived)	Low slopes indicative of Quaternary sediment accumulation, which creates ideal habitat for estuarine vegetation. Low slopes indicative of greater sediment deposition and wetland development, and less sensitivity to sediment movement. This is synonymous with mature estuaries exhibiting greater mangrove and saltmarsh development than immature estuaries (Roy et al., 2001), though applied at a smaller spatial scale.	High (3) Mod. (2) Low (1) Nil (0)	Quaternary geology + Slope > 5° Quaternary geology + Slope 2-5° Quaternary geology + Slope < 2° Bedrock geology
	Adaptive capacity (IAC)	Vegetation (Sydney's Salty Veg)	Mangrove (typically at lower elevations) is less sensitive to inundation changes due to improved capacity to build elevation through accretion and plant productivity, than saltmarsh. Based on relationships between elevation gain and vegetation within southeastern Australia (Rogers et al., 2005; Rogers et al., 2006). Adjoining upland vegetation sensitive to salinity changes (Greenwood & MacFarlane, 2006)	Low (3) Mod. (2) High (1) Nil (0)	Coastal Swamp Paperbark-Swamp Oak Scrub, Estuarine Swamp Oak Forest Saltmarsh, Estuarine reedland Mangrove Other Veg
Erosion (E1)	Exposure (EE)	Elevation	Lower elevations more exposed to erosive wave action.	High (3) Mod. (2) Low (1) Nil (0)	Elevation: 0–1 m or Marine sediments Elevation: 1–2 m Elevation: 2–5 m Elevation: > 5 m
	Sensitivity(ES)	Quaternary geology	Quaternary sediments more sensitive to erosion, particularly fine material associated with fluvial deposits, than bedrock geology.	High (3) Mod. (2) Low (1) Nil (0)	Fluvial sediments Estuarine sediments Marine sediments (undiff, anthro) Bedrock geology
	Adaptive capacity (EAC)	Vegetation	Mangrove has greater capacity to buffer wave action and accumulate sediments than saltmarsh (Kelleway et al., 2017a).	Low (3) Mod. (2) High (1) Nil (0)	Coastal Swamp Paperbark-Swamp Oak Scrub, Estuarine Swamp Oak Forest Saltmarsh, Estuarine reedland Mangrove Other Vegetation

classes are reported here as tidal flat, mangrove, saltmarsh, reedland, *Casuarina* for convenience. Areas categorised as Undifferentiated Regenerating Scrub, Urban Exotic/Native, Water, Artificial Wetland and Exotic Species within the acquired vegetation layer were individually examined and assigned a SLAMM category based upon elevation, position within the tidal frame and interpretation of aerial imagery from 2013 of the area (See Supplementary Table for information on alignment of vegetation classes with National wetland Inventory classes). In addition to vegetation classes, developed and undeveloped areas were delineated, as required for SLAMM. Developed areas were defined as built-up areas, including urban, industrial and commercial zones. These areas were delineated from the *Standard Instrument Local Environmental*

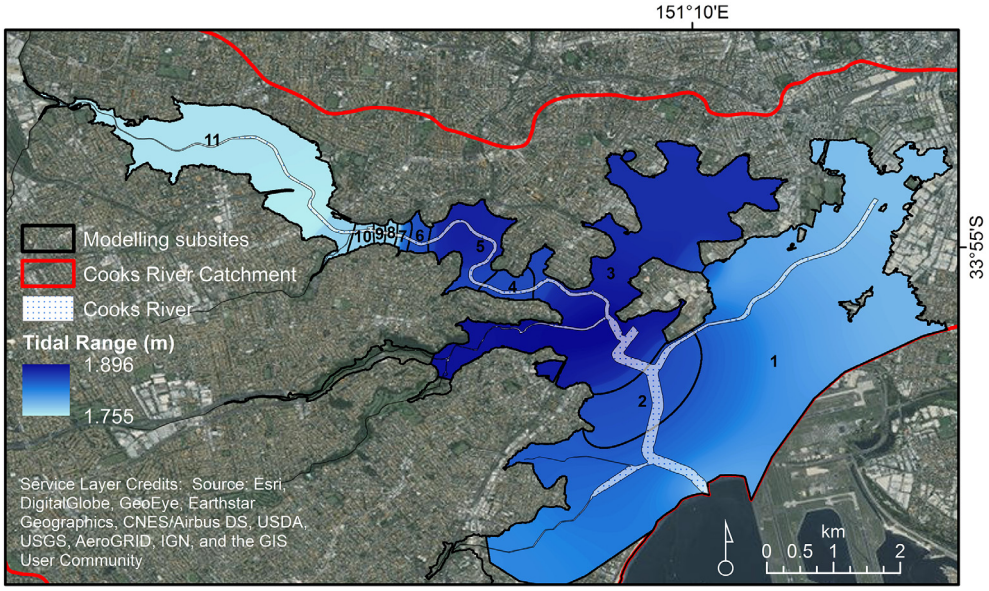

Fig. 2. Modelled tidal range surface and derived subsites (numbered 1–11) used within SLAMM. Outer line represents the modelling extent of the Cooks River study site.

Plan – Land Zoning (LZN) (DPE, 2013) and *Inner Sydney Regional Cadastral Survey* 2012 acquired from the Sydney Coastal Councils Group. Areas within the study site not classified as vegetation or developed were deemed to be undeveloped areas, that is, natural areas that contain no built-up zones. To ensure accuracy of mapped undeveloped areas, each area assigned this land use category was examined using high resolution aerial photography.

Within SLAMM, each vegetation class is assigned a certain elevation range within which it will typically occur. For this study, elevation ranges for each vegetation and land use category were assigned with respect to the tidal range, where the unit of measurement for elevation was the half tide unit (half of the tidal range set for a particular site), in order to account for the variation in tidal range and, thus, vegetation distribution with respect to elevation throughout the study site. Elevation ranges were determined based upon analysis of the 5 m DEM and derived slope surface with respect to the vegetation distribution at 2013. Further refinement of elevation boundaries was conducted during model calibration to ensure model error (the difference between modelled and observed vegetation distributions) at 2013 was no greater than 10%.

Accretion rates of wetland vegetation can be modelled in a variety of ways in SLAMM. Within this study, the accretion module was implemented. This module accounts for the spatial variation of accretion and various feedback processes that occur within wetlands. To account for the influence of surface processes of sediment accretion and subsurface processes, such as autocompaction of sediments and decomposition of organic material, on wetland elevations it was deemed more appropriate to utilise rates of surface elevation change in place of accretion rates to parameterise the accretion module. Consequently, the accretion module was parameterised on the basis of empirical relationships derived from Surface Elevation Table-Marker Horizons (SET-MH). The SET-MH technique utilises stable permanent benchmarks and marker horizons established within estuarine vegetation to analyse changes in elevation and accretion. SET-MH are the global standard for assessment of wetland responses to sea-level rise (Webb et al., 2013). A network of SET-MHs has been established along the south-east coast of Australia (Rogers et al., 2006). Due to their being no long term record of change in elevation and accretion of wetlands of the Cooks River, SET derived rates of surface elevation change were applied from a site of similar characteristics, Homebush Bay (Rogers et al., 2005). For mangrove and saltmarsh, these were modelled in relation to elevation, with a minimum of 0.1 mm/yr grading to 0.21 mm/yr in saltmarsh, and a minimum of 0.21 mm/yr grading to 2.63 mm/year in mangrove (Bowie, 2015).

Tidal data spanning the time period 1990–2013 were analysed and mean sea-level rise determined for the study site, estimated to be 2.8 mm/yr. This value was consistent with the global mean sea-level rise for the period 1993–2010 published by the IPCC (IPCC, 2013) and was utilised as the historic sea-level rise within SLAMM.

Once parameterised and calibrated for the study site, SLAMM was implemented to examine vulnerability of saltmarsh and mangrove under three sea-level rise scenarios. Based upon the IPCC Fifth Assessment Report (IPCC, 2013), a low (RCP 2.6), intermediate (RCP 4.5) and high (RCP 8.5) sea-level rise scenario were selected. These sea-level rise scenarios were time-adjusted to fit the modelling period, resulting in a projected rise of 0.322 m, 0.592 m and 1.022 m respectively to 2100 compared to 1990 sea level. Modelling was first conducted to simulate a scenario in which built-up areas were maintained over time (i.e. developed areas protected, thereby simulating the “coastal squeeze” of estuarine vegetation), prohibiting movement of vegetation to higher elevations designated as built-up areas. Keeping all parameters constant, an additional three scenarios (low, intermediate and high sea-level) were simulated in which built-up areas were permitted to convert to a vegetation class over time (i.e. developed areas unprotected and coastal squeeze effects minimised). Though such situations are completely hypothetical, as it is unlikely any management plan would consider allowing mostly urban areas to be removed in preference of vegetation, the simulations were used as an indication of the effects of coastal squeeze (Torio & Chmura, 2013). This was examined using ArcGIS (v.10.4.1) by determining the difference in modelled vegetation extent at 2100 when developed areas were maintained and when vegetation was permitted to occupy designated built-up areas. Spatial and statistical data on the conversion of vegetation and land use classes between the initial year of modelling, 2013, and 2100 was also conducted (i.e. change detection analysis). From such information, patterns of vegetation change and, by extension, the effects of sea-level rise on a variety of vegetation communities were able to be examined.

3. Results

3.1. Broad-scale vulnerability assessment

The assessment of erosion, inundation and vulnerability is subject to assumptions about flexibility in land-use conversion and future pathways for changes in vegetation distribution. The spatial distribution of estuarine vegetation vulnerability based on assessments assuming no changes in land-use and with vegetation distribution constrained to current extents, and possible future vegetation distribution presuming 90 cm sea-level rise, are illustrated in Fig. 3 for the Botany Bay region (see Supplementary figure for maps of entire study area).

The proportion of wetland exhibiting moderately high to high vulnerability was less than 13% of existing vegetation area and less than 8% of the potential future vegetation area when accounting for sea-level rise (Table 2). The proportion of wetland area assigned moderately high to high vulnerability based on potential future vegetation area was lower as landward areas that convert from other land-use to wetland will exhibit lower vulnerability due to their higher elevation, thereby resulting in a larger proportion of the future wetland area having moderate to low vulnerability. However, the absolute area identified as moderately high to high vulnerability increased by more the 50% when sea-level rise was incorporated in the assessment. Overall, it is probable that wetland area may increase substantially with sea-level rise providing land-use conversion is facilitated, and much of this increase is associated with areas of lower vulnerability.

3.2. Medium- resolution assessment of the Cooks River

Under the high sea-level rise model, approximately 199 ha of developed land was projected to convert to *Casuarina*, mangrove or freshwater wetland when allowed to do so (i.e. coastal squeeze effects were minimised: Fig. 4, Table 3). Under this scenario 9 ha of mangrove habitat converted to lower intertidal tidal flat. The overall pattern was the conversion of higher tidal range vegetation classes to lower tidal range vegetation classes or open water. Significant gains in mangrove extent were modelled to occur through the conversion of developed land (148 ha), undeveloped land (134 ha) and *Casuarina* (6 ha) to mangrove. However, reductions in saltmarsh extent were greater under a high sea-level rise scenario than the low scenario, declining to 16 ha, with 2.5 ha converting to tidal flat. Tidal flat increased in area by 33 ha with significant conversions from mangrove (9 ha), *Casuarina* (7 ha) and undeveloped land (13.36 ha) to tidal flat.

This contrasts with the outcomes of the low sea-level rise scenario. Developed land converting to wetland was only one-tenth of the high sea-level rise scenario, being 18 ha mostly converting to *Casuarina*. Under a low sea-level rise scenario there was projected to be virtually no loss of mangrove extent, and significant gains through the conversion of undeveloped land and *Casuarina* to mangrove. Saltmarsh area changed little, while *Casuarina* exhibited the largest change in area with 70 ha converting to mangrove under a low sea-level rise scenario.

When the planning assumption excluded the conversion of developed land to other classes the overall outcome for wetland vegetation

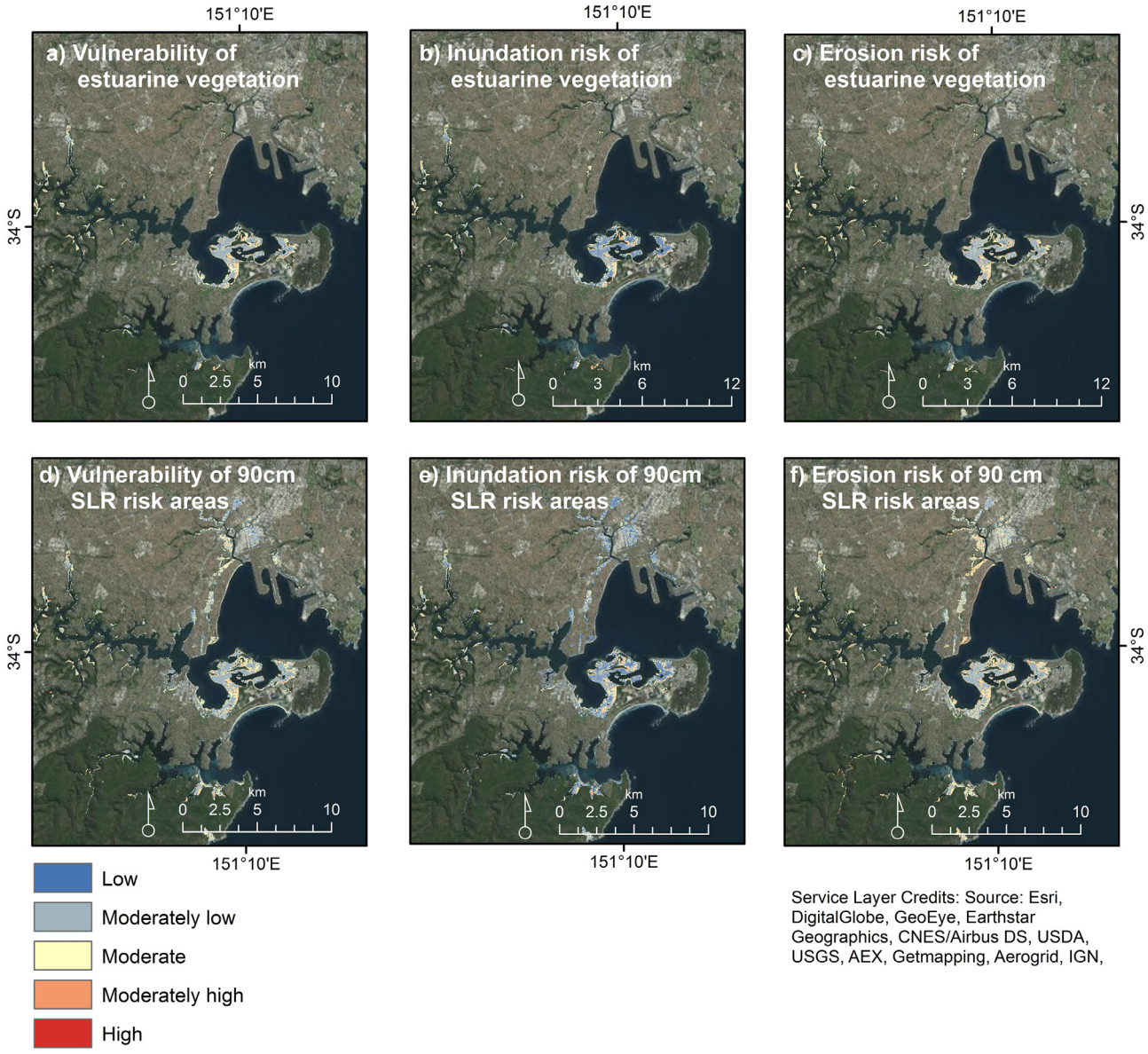
a) Vulnerability of estuarine vegetation
b) Inundation risk of estuarine vegetation
c) Erosion risk of estuarine vegetation
d) Vulnerability of 90cm SLR risk areas
e) Inundation risk of 90cm SLR risk areas
f) Erosion risk of 90 cm SLR risk areas
151°10'E
34°S
km
Low
Moderately low
Moderate
Moderately high
High
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN,

Fig. 3. a) Vulnerability assessment, and b) inundation and c) erosion assessment of existing estuarine vegetation at Botany Bay, and with a 90 cm SLR projection zone included (d, e and f, respectively).

Table 2
Area (ha) and proportion of total area (%) with low to high vulnerability. Estimates are based on the current distribution of estuarine vegetation, and possible vegetation distribution under a 90 cm sea-level rise projection scenario.

Vulnerability Class	Cell Score	Estuarine vegetation		Estuarine vegetation with 90 cm SLR projection	
		Area (%)	Area (ha)	Area (%)	Area (ha)
Low	1–3	52.45	3.29	267.66	6.07
Moderately low	4–7	682.34	42.79	2044.66	46.36
Moderate	8–11	658.91	41.32	1787.75	40.54
Moderately high	12–15	191.61	12.02	300.70	6.82
High	16–18	9.18	0.58	9.35	0.21
	Totals	**1594**	**100**	**4410**	**100**

was a reduction in wetland area (Fig. 4a and b). For example, under a low sea-level rise scenario the model projected a mangrove area of 51 ha, contrasting with an area of 77 ha when conversion of developed land to wetland vegetation was allowed; under a high sea-level rise scenario, these differences were exacerbated with only 130 ha of mangrove projected when developed land was protected from conversion compared to 292 ha when conversion of developed land to wetland vegetation classes was allowed. There was little difference in the outcome for saltmarsh between the model projection with or without conversion of developed land to vegetation classes, however the differences were substantial for *Casuarina* under both a high sea-level rise scenario (27 ha without developed land conversion, 78 ha with conversion of developed land), and low sea-level rise scenario (7.6 ha without developed land conversion, 46 ha with conversion of developed land).

4. Discussion

The first pass assessment provided a useful means of identifying areas that may convert to coastal wetland, particularly under future conditions of sea-level rise, and established that the Cooks River, one of the most heavily urbanised estuaries, offers significant opportunities for estuarine vegetation adaptation to sea-level rise, though the medium resolution analysis indicated that some vegetation communities fare

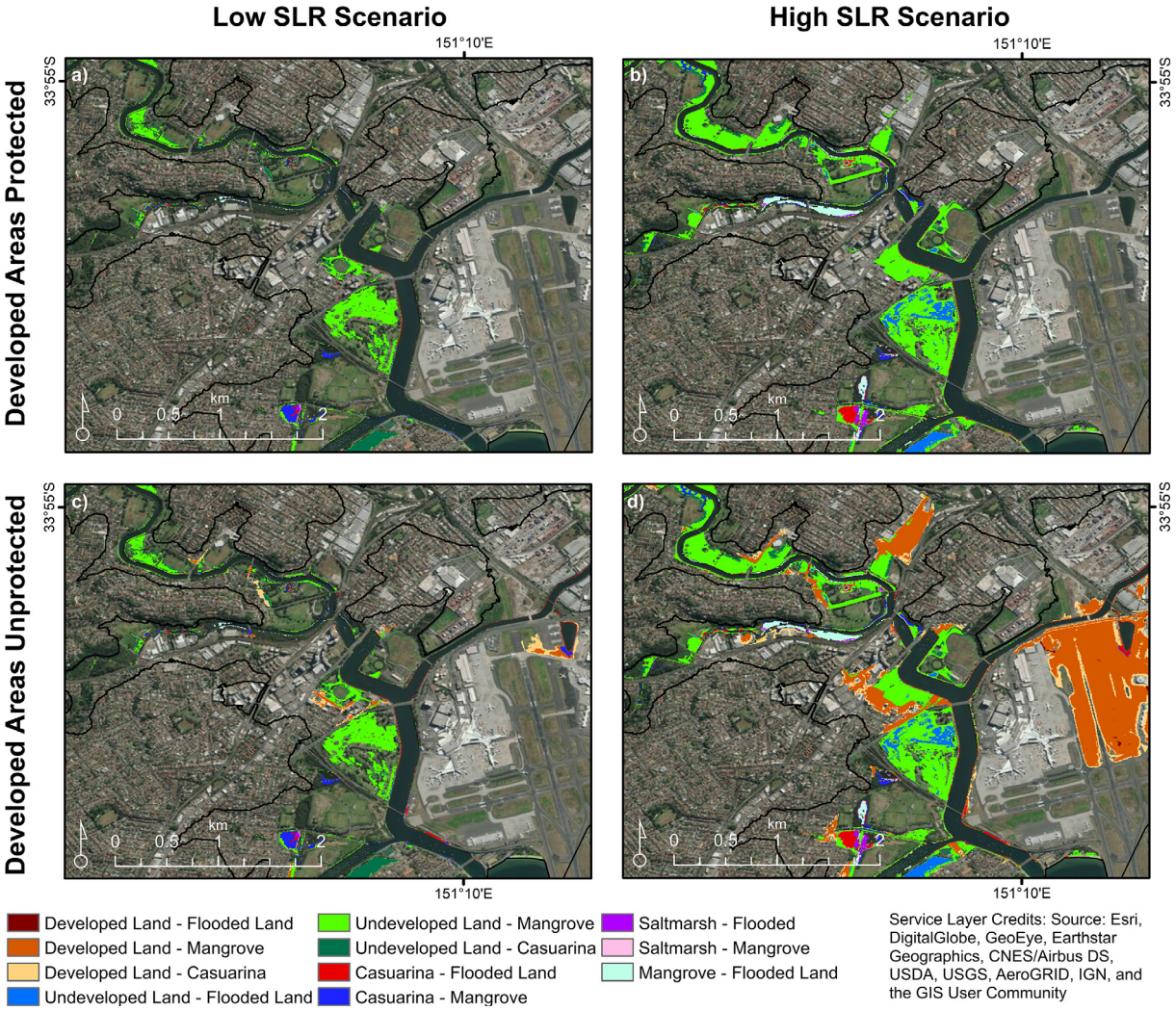

Fig. 4. Change detection analysis comparing current vegetation distribution (2013) with projected vegetation distribution (2100) under: a) low sea-level rise scenario with developed land protected from land use changes; b) high sea-level rise scenario with developed land protected from land use changes; c) low sea-level rise scenario with developed land able to convert to other land uses; and d) high sea-level rise scenario with developed land able to convert to other land uses.

better than others. When developed areas were unprotected, allowing for landward encroachment across a range of current land-uses (i.e. assuming no barriers emplaced), mangrove extent increased under all scenarios and was primarily limited to lower reaches of the Cooks River (Fig. 4). The best outcomes for mangrove extent were achieved under the highest sea-level rise scenario with developed areas unprotected; under these conditions mangrove was projected to increase by approximately 800% from a starting extent of 16 (ha). Conversely, saltmarsh extent diminished under the high sea-level rise scenarios and was restricted to the upper portions of tributaries. Saltmarsh extent was projected to decline between approximately 2–17% from a baseline extent of approximately 32 ha.

Actual outcomes for estuarine vegetation will therefore be profoundly influenced by land-use planning decisions. For example, the model projected conversion of part of Sydney Airport to mangrove under a high sea-level rise scenario or a complex of mangrove and *Casuarina* under a low-sea-level rise scenario, providing significant bird habitat; however both are likely to be prevented due to activities to safeguard infrastructure. In Sydney Harbour and its tributaries, seawalls armour in excess of 50% of the shoreline (Bulleri & Chapman, 2010) preventing landward migration. In other circumstances, however, there may be opportunities for the creation of "living shorelines" (Currin et al., 2010), which promote mangrove and saltmarsh extent and sea-level rise adaptation. To date, the living shorelines approach has not been widely utilised in Australia, despite benefits for coastal resilience as well as other ecosystem benefits, such as nursery habitat to threatened, commercially and recreationally important species, and carbon sequestration and storage (Davis, Currin, O'Brien, Raffenburg, & Davis, 2015; Gittman et al., 2015). Provided environmental factors such as geomorphology, hydrology and biogeochemical conditions (e.g. salinity) are appropriate, mangrove and saltmarsh species generally have a strong capacity to vegetate an intertidal area without active planting. Establishing new tidal wetlands or rehabilitating existing areas of estuarine vegetation has the resilience building benefit of binding sediments to limit erosion and enhances sediment trapping capacity by attenuating wave action (Duarte, Losada, Hendriks, Mazarrasa, & Marba, 2013). Further, tidal wetlands are also efficient sinks of greenhouse gases and may act to mitigate climate change (Duarte et al., 2013; Duarte, Middelburg, & Caraco, 2005).

The promotion of living shorelines is supported by recent policy developments. In November 2016, the Greater Sydney Commission released a draft amendment to the Greater Sydney Regional Plan entitled 'Towards our Greater Sydney 2056' (Greater Sydney Commission, 2016). The draft identified three major centres with both central Sydney and Parramatta within the estuarine zone and six distinct planning districts with four of these – North, Central, South and West Central – containing the vast majority of Sydney's estuaries. Sustainability priorities are focussed on maintaining landscapes, protecting

Table 3
Change in area (ha) of vegetation classes from 2013 (columns) to 2100 (rows) based on planning assumptions that developed land is either protected or unprotected from land cover conversion, and high and low sea-level rise scenarios.

		Vegetation Class		Developed Land	Undeveloped Land	*Casuarina*	Saltmarsh	Mangrove	Tidal Flat	Estuarine Water
				2013						
Develop Areas Unprotected	Low SLR Scenario (RCP 2.6)	Developed Land	2100	1975.39	0	0	0	0	0	0
		Undeveloped Land		0	509.51	0	0	0	0	0
		Casuarina		9.87	13.35	20.65	0	0	0	0
		Saltmarsh		0	0	0	18.71	0	0	0
		Mangrove		8.50	45.91	8.51	0.17	16.12	0	0
		Tidal Flat		0	0.17	2.08	0.22	0.83	0.20	0
		Estuarine Water		0	0	0.36	0	0	0.01	120.03
	High SLR Scenario (RCP 8.5)	Developed Land		1793.90	0	0	0	0	0	0
		Undeveloped Land		0	413.48	0	0	0	0	0
		Casuarina		50.25	7.74	17.07	0	0	0	0
		Saltmarsh		0	0	0	15.95	0	0	0
		Mangrove		147.61	133.74	5.90	0.60	7.42	0	0
		Tidal Flat		0.58	13.36	6.77	2.51	9.16	0.01	0
		Estuarine Water		0.10	0.03	1.85	0.03	0.40	0.21	120.03
Develop Areas Protected	Low SLR Scenario (RCP 2.6)	Developed Land		1993.77	0	3.09	0	0.52	0.02	0
		Undeveloped Land		0	509.51	0	0	0	0	0
		Casuarina		0	13.35	20.65	0	0	0	0
		Saltmarsh		0	0	0	18.71	0	0	0
		Mangrove		0	45.91	6.52	0.17	15.67	0	0
		Tidal Flat		0	0.17	1.32	0.22	0.79	0.20	0
		Estuarine Water		0	0	0.03	0	0	0	120.03
	High SLR Scenario (RCP 8.5)	Developed Land		1993.77	0.00	3.09	0	0.52	0.02	0
		Undeveloped Land		0	413.48	0.00	0	0	0	0
		Casuarina		0	7.74	17.07	0	0	0	0
		Saltmarsh		0	0.00	0.00	15.95	0	0	0
		Mangrove		0	133.74	5.29	0.60	7.23	0	0
		Tidal Flat		0	13.36	5.31	2.51	8.84	0	0
		Estuarine Water		0	0.03	0.84	0.03	0.39	0.20	120.03

waterways, protecting and enhancing biodiversity, building up our resilience against climate change and creating a 'Green Grid' across Greater Sydney. Two central tenets of the 'Green Grid' approach are to integrate management of the coast and the land; and improve public access to waterway foreshores, wetlands and riparian corridors. More specifically, the Draft South District plan identifies three priority Green Grid Projects, all of which have implications for estuarine vegetation adaptation.

i. *Cooks River Open Space Corridor* aims to become a regionally significant parkland corridor, with improved water quality and high quality open spaces linking Strathfield and Sydney Olympic Park, through Canterbury, Marrickville and Wolli Creek.
ii. *Wolli Creek Regional Park and Bardwell Valley Parkland* aims to provide open space for recreation, walking and cycling trails, connected patches of ecologically significant vegetation and improved water quality and stormwater management.
iii. *Salt Pan Creek Open Space Corridor* aims to enhance access to the corridor and improve trails and recreational opportunities.

The Central District Plan makes a special mention of maximising benefits to the public from the innovative use of golf courses, setting the action to *identify opportunities for shared golf courses and open space*. Where golf courses abut waterways, opportunities exist to improve integration with the natural environment, including estuarine vegetation, into the design of these areas in the future. The areas projected in this study to support large extents of mangrove correspond to the current distribution of sporting fields and golf clubs, including Marrickville Golf Club and Kogarah Golf Club, where the tidal range of the Cooks River is typically higher than elsewhere, and would therefore create more accommodation space for estuarine vegetation (Fig. 2). The utilisation of existing open spaces may provide the most feasible opportunities for supporting the establishment of estuarine vegetation in the future. Opportunities may also exist to utilise 'surplus' industrial lands, purchase private land, or develop agreements with private landholders for the purpose of conversion to estuarine vegetation.

Modelling outputs indicated that the best ecosystem outcomes were achieved when wetlands were positioned higher within the tidal frame. High elevation intertidal wetlands possess 'elevation capital' (Cahoon & Guntenspergen, 2010; Lovelock et al., 2015), which provides for a longer period of time over which a deficit between elevation gain, achieved through accretion and plant productivity, and sea-level rise can be tolerated. This is particularly important for saltmarsh which exhibits a very narrow elevation range and is vulnerable to encroachment by mangrove at lower elevations (Saintilan & Rogers, 2013) and *Casuarina* at higher elevations. Improving elevation capital and maintaining optimal positions within the tidal frame can be enhanced by applying thin layers of sediment to wetland surfaces that are typically sourced from dredge spoil (Ford, Cahoon, & Lynch, 1999; La Peyre, Gossman, & Piazza, 2009). This technique has yet to be applied in Australia, but is commonly used throughout the USA to improve wetland resilience (Stagg & Mendelssohn 2011; Anisfeld, Hill, & Cahoon, 2016). In urban areas, excavated sediment from building works may provide a low-cost and relatively contaminant-free source of sediment nourishment. Sediment derived from building sites offers additional advantages as the industrial history of Sydney's estuaries (particularly the upper Parramatta River, Cooks River and sections of the Georges River) means that estuarine sediments are likely to be contaminated. Opportunities for sand nourishment using offshore marine sand resources have been scoped and offer an additional sediment source

(AECOM, 2010).

Sediment nourishment may be particularly relevant where there are limited opportunities for estuarine vegetation expansion to higher elevations, either due to topographic or land use constraints (Stagg & Mendelssohn, 2011). The largest area of intertidal wetland in the region (the Kurnell Peninsula) occupies marine deltaic sands, receiving little terrigenous input. While there are opportunities for landward encroachment at this site, the elevation of existing wetland might be subsidised by the deposition of dredge-spoil associated with the nearby Port Botany. The dredging of estuary entrances in support of navigation might also provide material for the nourishment of marine deltaic wetlands (VanZomeren, Berkowitz, Piercy, & White, 2018). Within incised valleys, such as Wolli Creek, Middle Harbour and Lane Cover Rivers, the steep terrain and infrastructure constraints (e.g. train line and high-density housing) may make sediment nourishment the most viable, cost effective option for preservation of estuarine vegetation ecosystem services. As there is little evidence to indicate that mangrove removal will enhance saltmarsh resilience, active management through sediment nourishment may be the only viable option where SLAMM modelling indicated high potential for mangrove expansion to higher elevations in Cooks River and Wolli Creek, but not for saltmarsh.

Rezoning of foreshore and low lying areas could be used to increase the horizontal space for wetland migrations and to establish living shorelines (Gittman et al., 2015). While this may reduce the footprint available for development, this will predominantly be in areas of already high inundation and flooding risk. Further, an effective living shoreline will act as a buffer to sea-level rise for surrounding development areas (Davis et al., 2015), while enhancing ecologically significant habitat (Gittman et al., 2016; Bilkovic, Mitchell, Mason, & Duhring, 2016) and carbon sequestration (Davis et al., 2015). Development of living shorelines will also increase the extent of open green space, which is currently lacking in the area and could be integrated with plans to increase foreshore access and amenities.

Tools to enable living shoreline creation may include land buy-back and/or land exchange (Rogers et al., 2016). Other incentives for private stakeholders may include floor space bonuses, whereby developers may negotiate additional planning provisions, such as an increase to number of levels allowed in their development consent, in return for provisions which improve environmental or community benefits related to the project. These provisions could include conversion of a portion of their landholding to living shoreline and/or the implementation of water sensitive urban design which improves the habitat and sea-level rise resilience of adjoining wetlands. Growing global interest in the utilisation of market-based schemes to facilitate tidal wetland establishment, restoration and conservation could be explored (Rogers et al., 2016). This is largely founded upon the emerging knowledge that 'blue carbon' ecosystems, namely mangrove, saltmarsh and seagrass areas, may be stores of significant preserved carbon stocks, mostly in their soils and below-ground biomass, and may accumulate carbon at a faster rate than most terrestrial ecosystems (McLeod et al., 2011). The Australian government is currently investigating blue carbon opportunities both within its National Greenhouse Gas Inventory (NGGI) and its Emission Reduction Fund (ERF), while its role in the recent establishment of the International Blue Carbon Partnership (IBCP) also points to a promising future (Kelleway et al., 2017b).

5. Conclusions

Our modelling of sea-level rise impacts and adaptation options focussed on one of Australia's most densely urbanised estuaries. Contrary to expectation, the broad-scale vulnerability assessment demonstrated the potential for increases in estuarine vegetation extent. It also identified the potential capacity for mangrove to expand landward and longitudinally along estuaries when barriers to their establishment were limited and accommodation space was available. Medium-resolution modelling projected significant increases in mangrove extent under a range of sea-level rise scenarios when estuarine vegetation was able to maintain their position within the tidal frame. Critically, however, significant declines in the extent of mangrove and saltmarsh were projected when built-up areas were not able to convert to other land-use classes, specifically estuarine vegetation. This effect was most pronounced under the high sea-level rise scenario. Modelling demonstrated that saltmarsh is particularly vulnerable in the Sydney region, with previous research also identifying links between changes in relative sea level and the expansion of mangrove into saltmarshes. Specific consideration of saltmarsh conservation and actions to improve resilience are therefore appropriate.

Given the ever-broadening urban footprint resulting from the concentration of populations in coastal cities, it is important to note that coastal wetland ecosystems can still be accommodated, even in the context of anticipated sea-level rise. We have identified four potential adaptation options broadly applicable: i) eliminate or reduce non-climate stressors to enhance the resilience of existing ecosystems; ii) protect existing estuarine vegetation through engineering activities, including modification of existing structures where appropriate; iii) maintain the position of estuarine vegetation within shifting tidal prisms as the sea rises through thin-layer sediment nourishment; and iv) plan for living shoreline establishment and migration. The application of these strategies should provide sufficient opportunity for the preservation of coastal wetland habitat, and the considerable ecosystem benefits they provide to urban populations.

Acknowledgements

We thank the Sydney Coastal Councils Group for funding the research. KR receives funding from the University of Wollongong Global Challenges Program and the Australian Research Council (FT130100532).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2018.09.022.

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